ISABE 2003-1200

The Role of Thermodynamic Work Potential in Aerospace Vehicle Design

Dr. Bryce Roth*
Aerospace Systems Design Laboratory
Georgia Institute of Technology

Abstract

Thermodynamic performance is a prime consideration in the design of vehicles. This is because all vehicles operate by transforming the stored work potential contained in fuel into useful work. This work output is then used to overcome various loss mechanisms in the engine, drivetrain, and vehicle systems. A significant part of vehicle engineering is finding means to minimize losses integrated through the design mission in order to minimize costs. This paper discusses how thermodynamic work potential can be used as a vehicle analysis tool to minimize losses and improve performance. The foundation of this method is the second law of thermodynamics. This approach provides a "universal figure of merit" with which to measure performance, allows the integration of thermodynamic and mass properties aspects of vehicle engineering, provides a means to link thermodynamic losses to monetary costs, and provides a framework for evaluation of new technologies.

Introduction

The art and science of vehicle design is one of the most challenging engineering endeavors undertaken by mankind. All truly good vehicle designs are always a compromise between competing aspects of design merit including thermodynamic performance, weight, cost, maintainability, etc. It is precisely this need to balance the many facets of design performance that makes vehicle design challenging. A necessary prerequisite to achieving this balance is an understanding of the *fundamental nature* of the trades involved and knowledge of the exact cost (in terms of performance, weight, and dollars) of every decision made during the design process. Since design trades are the crux of the vehicle design process, one can imagine that it is desirable to create general vehicle analysis techniques to facilitate this process. Better still if such techniques use intuitive and easily understood principles based on fundamental physics that are applicable across *all* modes of transport, not just a select few.

This may at first seem an untenable need. However, all vehicles must obey the same laws of physics and are subject to the same fundamental limitations. Given this situation, there *must* be a common thread of analysis applicable to all classes of vehicle. Specifically, if all vehicles must obey the same laws of physics, then *there must be a common figure of merit* applicable to any vehicle, and it should be possible to formulate a *generalized theory of vehicle design* based on these fundamental principles.

The fundamental principles most applicable to vehicle deign are Newton's Laws of motion and the Laws of Thermodynamics. Newton's Second Law and the First Law of Thermodynamics are the cornerstones upon which virtually all vehicle analysis methods are built today. The other laws play a supporting role, but have not generally been applied to the same extent. In particular, the second law of thermodynamics has never been central to the vehicle design process, but holds considerable promise as a fundamental principle to guide vehicle designers to better designs in the future.

The reason that the second law is a promising tool for vehicle designers is that it implies the concept of *thermodynamic work potential*. To understand this, consider that all vehicles must consume work potential of some form in order to move. At the most fundamental level, it is the usage and loss of thermodynamic work potential that drives virtually *every* aspect of a vehicle's design and performance. Yet, modern vehicle design methods make little or no formal use of the second law of thermodynamics and the work potential concept it suggests.

In short, *there simply is no rational and organized method in place today to enable the estimation and tracking of work potential usage in vehicle design*, even though work potential is the lifeblood of vehicular motion! In fact, most vehicles in cruising operation create nothing but loss—there is no significant storage of work potential. It follows that losses are an important driver in vehicle design. Application of work potential concepts to vehicle design is the key to enabling calculation of the magnitude of the work loss incurred in each thermodynamic process relevant to a vehicle's operation such that the most significant sources of loss can be identified and targeted for improvement. This is especially true for high-speed vehicles where the losses associated with high-speed flow processes can easily become exorbitant if not properly addressed.

The need to accurately calculate loss of work potential relative to a thermodynamic ideal has led to interest in methods employing the second law of thermodynamics as a basis for loss estimation. This approach is appealing because it provides an unambiguous definition of an ideal

*www.asdl.gatech.edu/prop

against which the actual process can be compared. Thus, whereas conventional analysis methods give information as to the flow of *energy*, a second law-based method enables calculation of *work potential*. This capability will facilitate the creation of analytical models to identify and track all sources of thermodynamic loss in an entire vehicle or subsystem. Such an approach would make it possible to estimate the *absolute* loss associated with each loss mechanism in terms of a *single figure of merit* (FoM) applicable to *all* vehicle components and processes.

The objective of this paper is to describe recent research developments in work potential methods for aerospace vehicle design. The paper begins with a broad definition of thermodynamic work potential and relates this to several specific work potential FoMs that have been suggested by various authors. Next, the merits and useful attributes of work potential for aerospace vehicle design are discussed extensively. Finally, a formal loss management method for vehicle analysis is described that enables comprehensive analysis of vehicle loss.

A General Definition of Work Potential

In the broadest sense, that which we think of as work potential is thermodynamically related to equilibrium (in a physical, chemical, thermal, or any other sense). Specifically, the *farther a given substance is out of equilibrium with its environment, the greater its potential to do useful work*. The higher a rock is on the hill, the more work can be extracted in taking it to the bottom of the hill. The stronger the wind blows, the more energy can be extracted in decelerating it relative to the ground. It is the constant state of non-equilibrium that drives the world around us. This concept of equilibrium is intimately linked with the second law of thermodynamics, and the analytical techniques developed to quantify work potential are referred to as second-law methods.

A substantial body of work has appeared in the past several decades dealing with second-law approaches to measuring work potential and loss thereof. One such measure of work potential is exergy.[1] Exergy is the best-known and most formalized measure of work potential available today.[2,3,4] Put simply, *exergy is a thermodynamic state describing the maximum theoretical (Carnot) work that can be obtained from a substance in taking it from a given chemical composition, temperature, and pressure to a state of chemical, thermal, and mechanical equilibrium with the environment*. The general definition of exergy is given by:

$$Ex \equiv H - H_{amb} - T_{amb}\left(S - S_{amb}\right) + \left(\text{Other Terms}\right) \qquad (1)$$

In this case, the "other terms" are used to denote exergy due to kinetic energy, potential energy, chemical potential, radiation, heat transfer, etc. Note that while energy is a conserved quantity, exergy is *not*, and is always destroyed when entropy is produced. Note also that the definition of exergy depends on the ambient environment. A considerable body of literature exists describing the theory and application of exergy analysis, and references 1, 5, 6, 7, and 8 are well-known texts on the subject.

Another work potential FoM that has been proposed in the past is gas specific power of isentropic expansion (sometimes called gas horsepower), which was used by Nichols[9] as a work potential figure of merit for combustor loss. It is also used extensively as a figure of merit for gas generator power output, but has received little attention beyond this limited application. However, the concept of gas horsepower has great potential as a general work potential FoM in engine analyses of all types, and is discussed further in references 10 and 11.

A third figure of merit discussed extensively by Curran and Craig[12] is based not on energy, but force (thrust), known as the stream thrust concept. This involves calculation of stream thrust potential (also known as specific thrust) at each flow station and optimizing the cycle to deliver the highest stream thrust potential. Later, Riggins[13] extended this concept by introducing the "lost thrust method" that allows accurate calculation of stream thrust loss due to inefficiencies. In addition, Riggins introduced the thrust work potential and lost thrust work potential figures of merit and showed that optimization of exergy output does not necessarily lead to the best propulsive cycle from a thrust production point of view.

The point of this discussion is that there is more than one way to measure work potential. Each of the work potential figures of merit previously mentioned is useful for particular types of loss analysis, with each differing from the next in the basic assumptions implied in their respective definitions. Exergy is the most general work potential FoM, providing an absolute upper limit of work potential set by the bounds of the second law of thermodynamics. It is measured with respect to equilibrium with ambient temperature and pressure. Gas horsepower is the work potential obtained from isentropic expansion to ambient pressure, but does not enforce temperature equilibrium, and is therefore a special case of exergy. Thrust work potential measures the capacity to produce thrust work relative to a prescribed reference frame via isentropic expansion of a gas, and is a special case of gas horsepower. More discussion on the definitions of and differences between the various measures of work potential is available in references 14, and 15. Suffice it to say that a rich variety of tools is available with which to measure losses in vehicle systems. The second law of thermodynamics and the work potential FoMs it suggests are the foundation that enables the creation of more comprehensive vehicle loss management methods than are presently available.

Useful Attributes of Work Potential for Vehicle Design

The concept of work potential is naturally suited to aerospace vehicle design. The potential applications these techniques have towards simplifying and improving vehicles is only now beginning to be explored. This section will point out a few of the features that make work potential methods useful in vehicle design and, where possible, illustrate their application.

The Limits of Design Perfection

One of the most basic advantages of viewing vehicle aerothermodynamic performance in terms of work potential is that it inherently focuses all attention on what the *absolute magnitude* of loss is in the vehicle's systems and unambiguously identifies the source of each loss. It becomes immediately obvious using the work potential method how much improvement is possible and how close the actual system is to ideal. Moreover, it is immediately evident which components of the system are causing the most loss, thereby attracting attention to those areas where the most improvement is possible. In short, *the concept of work potential is as fundamental to defining the limits of vehicle design as Carnot cycle is to defining the limits of thermodynamic performance*.

This is illustrated in Figure 1 for an example using the Northrop F-5E fighter aircraft. This figure depicts the breakdown of total exergy usage throughout the F-5E's design mission (a subsonic area intercept of 225 nmi radius). In flying this mission, the F-5E consumes 4,400 lbs of JP-8 fuel. This JP-8 has some work potential inherently stored in it, which is released by combustion in the engine. Of the work potential (exergy) initially stored in the fuel, the left side of Figure 1 shows that roughly 90% of it is destroyed as losses in the propulsion system. The top right of this figure shows that the vast majority of these propulsive losses consist of exhaust heat, irreversible combustion, and residual kinetic energy of the jet efflux left in the wake of the vehicle. The remaining 10% of the exergy is converted into thrust work and used to overcome vehicle drag (lower right). This is a perspective that is seldom noted, even by experienced designers: *from a exergy (work potential) perspective, the vast majority of losses in most aerospace vehicles occur in the propulsion system*. It is abundantly clear based on this figure that there is much to be gained by concentrating on reducing propulsion system losses.*

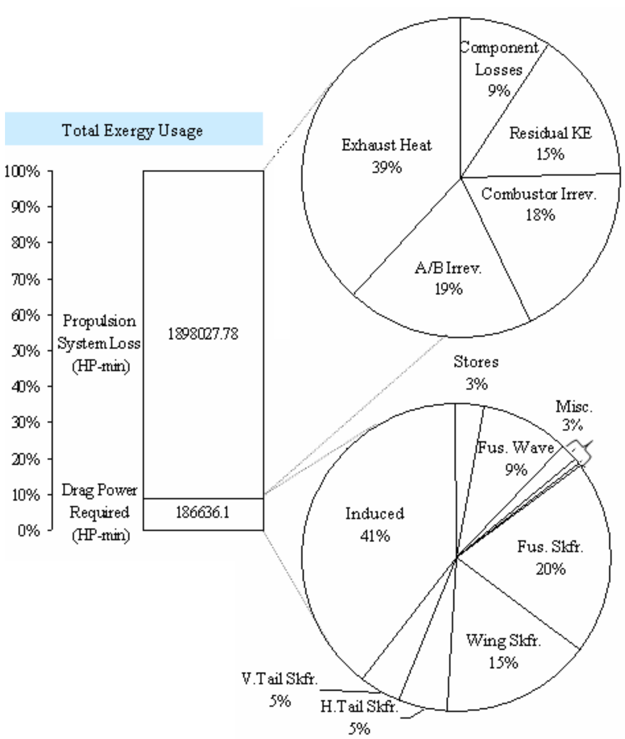


Figure 1: Total Exergy Usage During F-5E Subsonic Area Intercept Mission.

A "Universal Currency" for Vehicle Design

The traditional measure for design merit for engine and vehicle components is "efficiency." There are nearly as many definitions for efficiency as there are types of components in engines and vehicles. Thermodynamic work potential has advantages over traditional efficiencies as a measure of performance in that work potential is a more fundamental quantity directly related to the physics of the problem. In fact, work potential is an extensive *thermodynamic property* of a substance, in the same sense that enthalpy, entropy, etc. are thermodynamic properties. Consequently, work potential has the same definition for all thermodynamic processes, regardless of the physical component. In other words, a loss of 1 unit of work potential in an engine compressor is the same as a loss of 1 unit of work potential in the combustor, turbine, air conditioning packs, radar, or *any* other system. This is in contrast to the conventional system of component efficiencies wherein 1 point of compressor efficiency is *not* equivalent to 1 point of turbine efficiency, etc. This point is punctuated in Table I, which lists an abbreviated subset of the component efficiencies typically used in aircraft engines. Each component efficiency is unique and cannot be directly compared to any other efficiency. However, as this table shows, the work potential viewpoint does not suffer any such handicap: all component losses can be directly compared to one another on an "apples to apples" basis. It therefore seems logical to presume that the concept of work potential can be used as a common figure of merit (FoM) for judging the absolute value of losses compared amongst disparate components and thermodynamic

* Incidentally, these losses can be reduced by introducing technologies that allow the engine to operate at higher overall pressure ratios and higher turbine inlet temperatures, as has been the trend for many years.

Table I: Comparison of Commonly Used Engine Efficiencies to Their Equivilent Work Potential FoMs.

Component	***Classical Efficiency***	***Work Potential Equivalent***
Inlet	$\text{Inlet Pressure Recovery} \equiv \dfrac{\text{Inlet Discharge Stagnation Pressure}}{\text{Freestream Stagnation Pressure}}$	Loss in Work Potential
Compressor	$\text{Compressor Efficiency} \equiv \dfrac{\text{Ideal Compression Work Required}}{\text{Actual Compression Work Required}}$	Loss in Work Potential
Combustor	$\text{Combustion Efficiency} \equiv \dfrac{\text{Actual Combustion Heat Release}}{\text{Ideal Combustion Heat Release}}$	Loss in Work Potential
Combustor	$\text{Combustor Pressure Loss} \equiv \dfrac{\text{Combustor Discharge Pressure}}{\text{Combustor Inlet Pressure}}$	Loss in Work Potential
Turbine	$\text{Turbine Efficiency} \equiv \dfrac{\text{Actual Expansion Work Produced}}{\text{Ideal Expansion Work Produced}}$	Loss in Work Potential
Nozzle	$\text{Nozzle Thrust Coefficient} \equiv \dfrac{\text{Actual Jet Thrust}}{\text{Ideal Jet Thrust}}$	Loss in Work Potential

processes.[16] In short, *just as a viable country must have a common currency to facilitate commerce and trade, so must aerospace vehicle design have a common currency to facilitate design trades*. Thermodynamic work potential is the "universal currency" of aerothermodynamic performance that is needed for aerospace vehicle design.

The bridge between Aero-thermo Performance and Vehicle Weight (Mass)

It was mentioned that one can think of mission fuel as being a form of stored work potential, which implies that there must be a relationship between mission fuel weight and usage of thermodynamic work potential. In other words, there must be a relationship between *aerothermodynamic performance* and *weight*. In fact, thermodynamic performance and vehicle mass properties (weight) can be quantified in terms of a single interchangeable figure of merit using loss management methods described later in this paper.

To understand this link, consider vehicle performance from a thermodynamic point of view. The work used for vehicle motion must come from the work potential stored in the fuel. Furthermore, there must be a one-to-one correspondence between fuel weight and total usage of work potential (loss incurred) during the mission. Therefore, *it should be possible to quantify losses incurred during the mission (such as drag work, engine inefficiencies, etc.) in terms of the fuel weight required to offset those losses*. This is the crux of the loss management concept introduced in the next section: *to quantify aerothermodynamic aspects of design performance in terms of fuel weight chargeable to each individual source of loss*. The result is effectively a unified weight/performance vehicle analysis method.[17]

This relationship between vehicle weight and thermodynamic performance is further illustrated in Figure 2, which depicts the work potential (or fuel) flow rate at several points in a generic aircraft mission. At every instant in time, the fuel work potential is converted

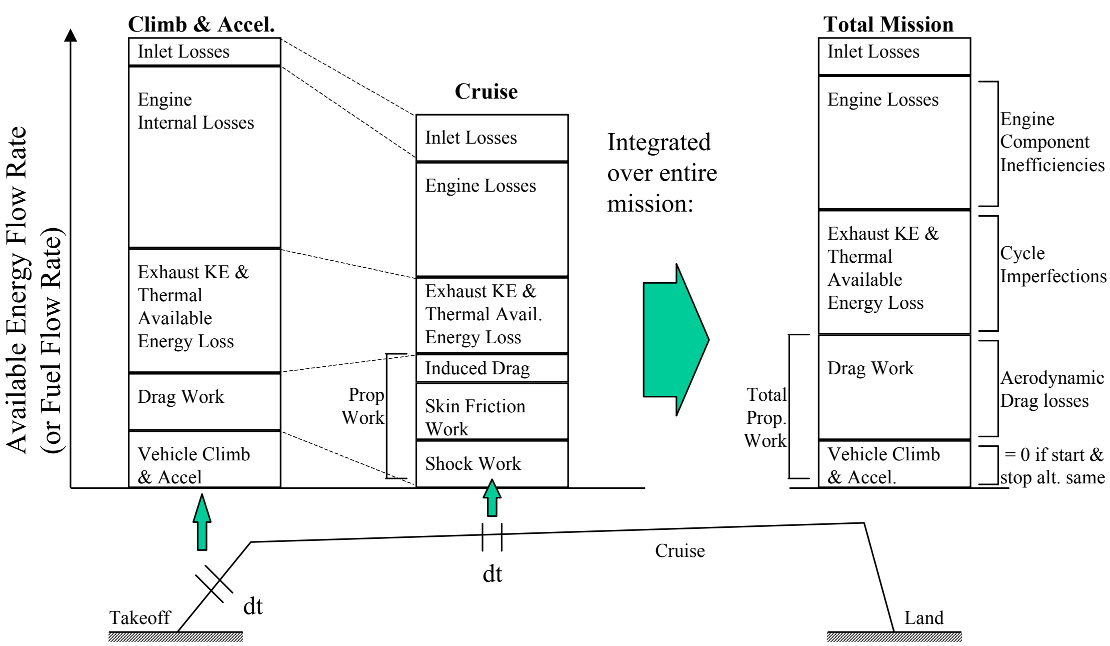


Figure 2: Integration of Instantaneous Work Losses Through an Aircraft Mission to Obtain Total Loss.

into either airframe kinetic/potential energy or atmospheric heat. For instance, a portion is lost as engine exhaust heat, and an additional increment is lost as heat due to component inefficiencies in the engine. A portion of the energy is lost as kinetic energy in the exhaust flow due to the fact that propulsive efficiency is less than unity. Finally, the useful thrust work on the airframe must either be dissipated in the atmosphere as drag work, or be stored as airframe kinetic/potential energy.

It is possible to integrate these losses over the entire mission to yield an estimate of the total work performed and loss thereof. More importantly, if each individual "sink" of work potential is accumulated separately during the integration process, the result is detailed knowledge about the total thermodynamic cost of each loss and storage mechanism (as was shown in Figure 1 for the F-5E). If all work potential consumed during the vehicle mission comes from fuel carried on board the vehicle, it should be possible to translate these losses into a corresponding quantity of fuel burned to overcome each source of loss. In effect, the loss stack-up is translated into a fuel weight stack-up, with each loss mechanism accounting for its own individual piece of fuel burn.

The implication of this idea is that *it is possible to use work potential methods to attribute not only vehicle empty weight, but also fuel weight to each functional component of the vehicle*. This idea is illustrated in Figure 3 for the Northrop F-5E example considered earlier. The left side of this figure shows a conventional gross weight breakdown wherein fuel weight is treated as a single lump sum, separate from the vehicle functional groups. The right side of this figure shows the *chargeable* gross weight breakdown for the F-5E as measured based on losses in thrust work potential (instead of exergy, as was used in the previous example). Note that the fuel weight in the latter scheme is bookkept with the functional components of the vehicle in accordance with how each component contributes to usage of work potential.

It is clear from Figure 3 that propulsion system losses account for more than a third of total mission fuel burn (recall that this was 90% when calculated using exergy). Therefore, while the propulsion system accounts for only 12% of the F-5E *empty* weight, it accounts for 24% of *gross* weight. Similarly, almost half of the F-5E fuel burn is chargeable to airframe-related losses, mainly aerodynamic drag. Consequently, the airframe itself accounts for 49% of vehicle gross weight. The remainder of the fuel weight is chargeable to fixed equipment and payload. The sum of component empty weight and chargeable fuel weight leads to the concept of *chargeable gross weight,* an ideal system-level figure of merit to unify thermodynamic performance and mass properties aspects of vehicle design.

Loss Accounting as a Means for Cost Accounting

Cost is the primary driver influencing the design, manufacture, and operation of future aerospace vehicles. Accurate and comprehensive accounting of vehicle life cycle costs (LCC) is therefore an important element needed for future aerospace vehicle design. The first step in controlling cost is understanding and accounting for its underlying sources. Thermodynamic work potential provides a ready-made, *physics-based* framework for allocation of manufacturing and operating costs, particularly fuel costs.

Consider the earlier statement that all the work potential initially stored in the fuel of an aircraft eventually appears as a loss. Therefore, the partitioning of work potential loss throughout the vehicle mission is what determines the partitioning of fuel cost. Fuel cost is one of the largest components of vehicle LCC, yet *the aircraft industry has no practical means of accounting for fuel cost chargeability*. Loss management methods based on the concept of thermodynamic work potential offer a comprehensive, consistent, physics-based means of allocating fuel cost chargeability to the underlying aerothermodynamic loss mechanisms.

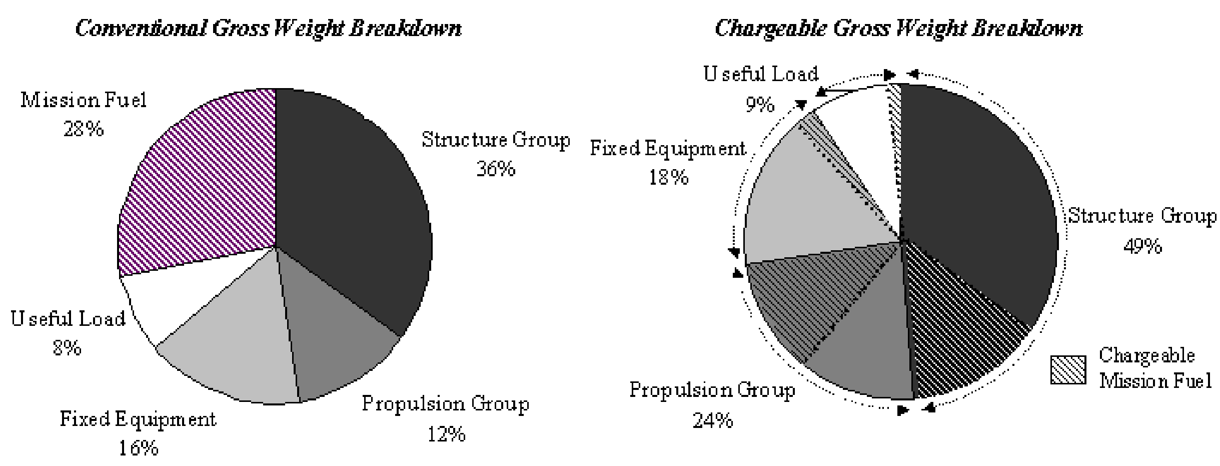


Figure 3: Comparison of Conventional Gross Weight Breakdown for the F-5E Versus Chargeable Gross Weight Breakdown (Thrust Work Potential FoM).

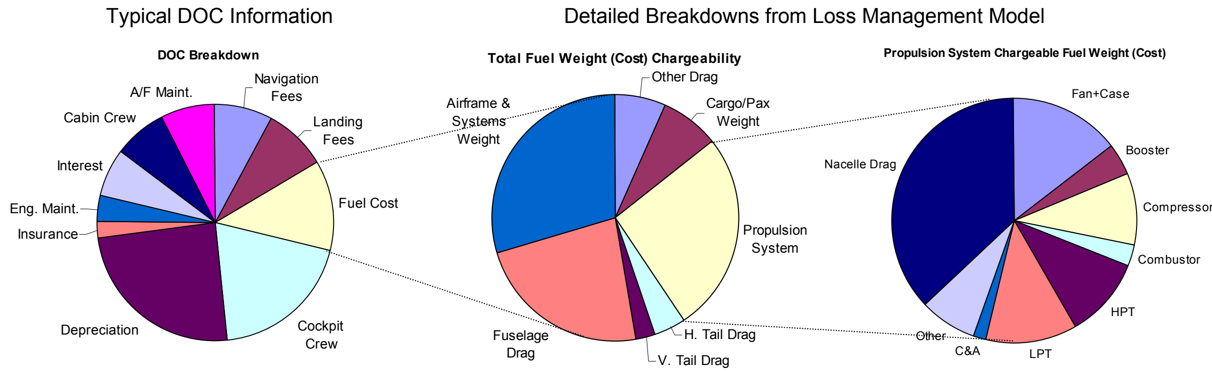


Figure 4: Allocation of Fuel Cost Chargeability to the Underlying Aerothermodynamic Loss Mechanisms.

This idea was recently demonstrated for a greatly simplified commercial aircraft example consisting of a Boeing 737-300 with CFM56-3C-1 engines. The results of the B737 loss management analysis are illustrated in Figure 4. The pie chart at far left shows a typical direct operating cost breakdown for the B737/CFM56, with approximately 20% of total operating costs being fuel costs. Using conventional analysis techniques, it is possible to estimate how much fuel is burned at each mission leg, but it is *not* possible to allocate fuel usage to any specific component or loss mechanism. This *is* possible when loss management techniques are used. The results are shown in the center pie chart. Note that airframe and systems weight are the single largest contributors to B737 fuel cost, accounting for approximately 35% of total fuel cost. Similarly, 25% of total fuel cost is chargeable to propulsion system losses (measured using gas specific power as the work potential FoM); of this ~15% is chargeable to losses in the compressor, ~5% to losses in the combustor, etc. Assuming the cost of fuel is $0.70/gal, the fuel cost due to compressor losses is $90.68 per trip. These results were *analytically generated* based on the *physics of the problem* and provide a wealth of information not otherwise available regarding the source and magnitude of fuel costs for the B737.

If component costs are assessed based on *chargeable gross weight* instead of component empty weight, one will obtain a more truthful estimate of the contribution that a particular component makes to total vehicle manufacturing cost. For example, a horizontal stabilizer contributes to manufacturing cost not only through the physical weight and materials used in its construction, but also through its contribution to drag. The drag requires an incremental increase in fuel weight for a given vehicle mission, and also corresponding adjustments in other parts of the airframe in order to accommodate the increased fuel load. It seems logical that one should track the total contribution of the horizontal stabilizer to vehicle cost based on mass properties and thermodynamic performance if possible. Unified mass properties/performance analysis using thermodynamic work potential provides a means for doing so.

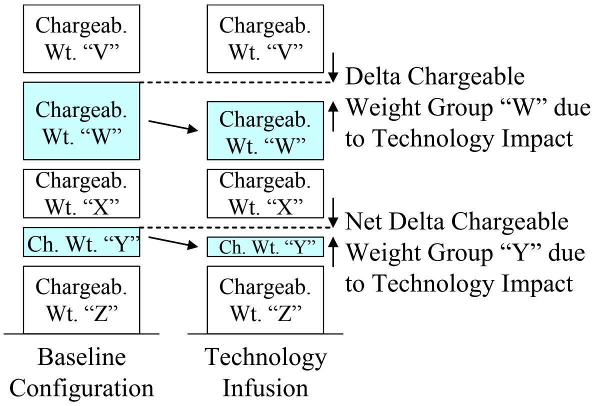
A Framework for Understanding Technology Impact

Integration and evaluation of advanced technology in tomorrow's highly complex and integrated vehicles is one of the most formidable tasks facing designers today. Technology integration is inherently a multidisciplinary problem requiring tremendous depth and breadth of knowledge to accomplish. Moreover, it is difficult to ascertain the true benefits of any individual technology when employed as part of a suite of advanced technologies installed in an advanced design or concept demonstrator. This is due to interactions amongst the technologies and because there is seldom a common figure of merit that captures both the weight and performance impact of a given technology.

Based on the development presented to this point, it should be clear that work potential methods have considerable potential to facilitate evaluation and selection of those technologies that impact vehicle aero-thermodynamic performance and/or weight. Specifically, the concept of gross weight chargeability can provide an integrated framework for multidisciplinary design wherein the aerothermodynamic cost and benefit of technology concepts can be explicitly evaluated. In effect, chargeable gross weight is a common measure for comparison of disparate performance metrics and technologies.

The typical method used to assess technology impact is to use perturbations from a baseline model. Sized vehicle empty weight and gross weight required to complete a specified mission for a baseline vehicle are determined using mission analysis. Subsequently, a mission model having modifications to account for advanced technology is analyzed for the same mission to arrive at a revised estimate for required empty and fuel weight to complete the mission. The difference between the two cases is taken to be the net effect of adding new technologies to the baseline design.

The scenario illustrated in Figure 5 represents the evaluation of that same technology in terms of chargeable gross weight groups. In this case, the baseline design



Detailed Understanding of Detailed Mechanisms that Cause Net Change: ***Understanding of Effect***

Figure 5: Illustration of the Differences Between Technology Impact as Estimated Using Gross Weight and Chargeable Gross Weight.

gross weight is partitioned into chargeable components using the unified weight/performance approach mentioned previously. Next, the same analysis is conducted on the advanced technology design. The differences between the chargeable gross weight groups constitute the technology impact. Therefore, in this hypothetical example, the proposed technology had an impact on chargeable gross weight groups "W" and "Y" (shaded), but had no significant impact on any of the other chargeable weight groups. The result is an understanding of the *underlying effect* that the technology has on each functional component as opposed to a description of the *net effect* at the system level.[18]

Loss Management Methods in Vehicle Design

Every vehicle must have some provision for production of useful work to propel it through its environment, regardless of its means of locomotion or the medium through which it passes. Therefore, the logical point of departure in the development of a general loss management methodology is the propulsion system. All propulsion systems function by transforming work

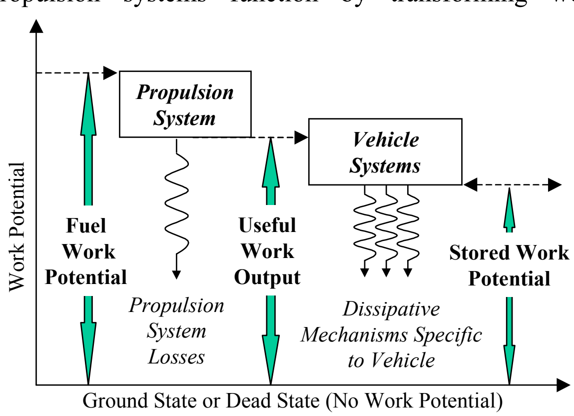


Figure 6: A Generalized Model of Work Potential Consumption for Vehicular Applications.

potential of some form into useful physical work, usually through action on a fuel of some type. For any given engine and thermodynamic cycle of interest, it is intuitively obvious (and has been thermodynamically proven)[7, 8] that the second law of thermodynamics places an upper bound on the maximum work that can be extracted from a fuel. Any deviation between the ideal engine power output and the actual engine power output constitutes a loss chargeable to the propulsion system. For most vehicles, the useful work produced by the engine is used to overcome various dissipative mechanisms specific to the vehicle itself. The work output that is not dissipated is stored in some form (kinetic energy of the vehicle, for example).

This idea is illustrated in Figure 6, which shows a diagrammatic representation of a very simple and general model for vehicle loss accounting. The origin of this figure corresponds to the ground state (or dead state) in which there is no potential to do work. The fuel work potential is shown at far left and initially has some finite potential to do work. It is then processed in the engine, at which point some of the work potential is dissipated while the remainder appears as useful work. A portion of this work output is in turn lost to dissipative mechanisms inherent to the vehicle itself, while the remainder is stored as some form of useful energy.

Thus, this simple model postulates three basic "sinks" of work potential available to a typical vehicle: losses due to the propulsion system, losses specific to the vehicle and its systems, and work storage mechanisms. The relative importance of these three sinks will vary according to the vehicle's function. For instance, vehicles designed for long range cruise (such as aircraft or ships) ultimately dissipate all of the fuel work potential into the atmosphere as heat, with little or none being stored as work potential of another form. Launch vehicles, on the other hand, store a great deal of the fuel work potential in the form of vehicle kinetic and potential energy at burnout. In an abstract sense, one can think of the propulsion system and entire vehicle as being nothing more than a transfer function that takes the work potential of the fuel into 1) losses and 2) useful energy stored in other forms.

The sum of propulsion system losses, vehicle-specific dissipative mechanisms, and work potential storage in the vehicle and its systems must be equal to the total work potential initially present in the storage reservoir (fuel tanks). Expressed mathematically:

$$\begin{aligned}(\text{Initial Work Potential}) = (\text{Propulsion System Losses}) &+ \\ (\text{Vehicle Losses}) + (\text{Final Work Potential})&\end{aligned} \tag{2}$$

Moreover, this rule must also hold for all times in between the start of the mission and any arbitrary intermediate time, t:

$$\left(\text{Work Potential Consumed}\right)\Big|_0^t = \int_0^t \sum_i \frac{\left(\text{Propulsive Loss}\right)_i}{dt} dt + \int_0^t \sum_j \frac{\left(\text{Vehicle Losses}\right)_j}{dt} dt + \int_0^t \sum_k \frac{\left(\text{Stored Potential}\right)_k}{dt} dt \quad (3)$$

where: t = mission time
i = counting index on # of propulsive losses
j = counting index on # of vehicle-specific losses
k = counting index on # work storage mechanisms

This simple model is the basis for development of a generalized vehicle loss management analysis method presented in the next section. It should be pointed out that the division of losses into propulsive and vehicle-specific components is somewhat arbitrary in that there is no thermodynamic difference between the losses. An alternative formulation of Eq. (3) would be to divide work potential usage into inherent and avoidable losses, with inherent losses being due to fundamental physics (such as exhaust heat loss in the engine), and avoidable losses being those which the designer has direct control over. There are many equally valid ways to partition losses, but the model presented in Figure 6 is the most convenient for practical vehicle analysis problems.

A General Methodology

The general methodology for construction of detailed loss management models is divided into four basic steps,[19] as shown in the flowchart of Figure 7. In brief, Step "0" in the construction of a loss management model is to explicitly define loss in a way most suited to the needs of the current analysis. It was previously mentioned that are a variety of ways to measure thermodynamic loss, and the choice of which to use depends on the situation at hand. When this is known and clearly understood, the step 1 is to clearly identify all loss mechanisms that are significant to the operation of the vehicle. This is done with the assistance of a functional decomposition tool known as a relevance tree, and the ultimate outcome is a detailed listing of all sources of loss.

Next, a mathematical representation of each loss source is created in step two, which necessarily requires extensive information on propulsion system and vehicle systems performance. The result of steps 0-2 is a differential loss model that describes the instantaneous loss breakdown of the vehicle as a function of operating condition. The construction of an accurate and complete differential representation of loss is an essential feature that enables the creation of vehicle loss management models.

Step 3 integrates this differential loss model through time over a single vehicle mission or duty cycle to obtain total loss chargeable to each loss mechanism. Obviously, it is imperative to use a vehicle mission that is representative of the operation that the vehicle will actually experience in service. Finally, one must assign chargeability for each loss to its underlying source. The objective of step 4

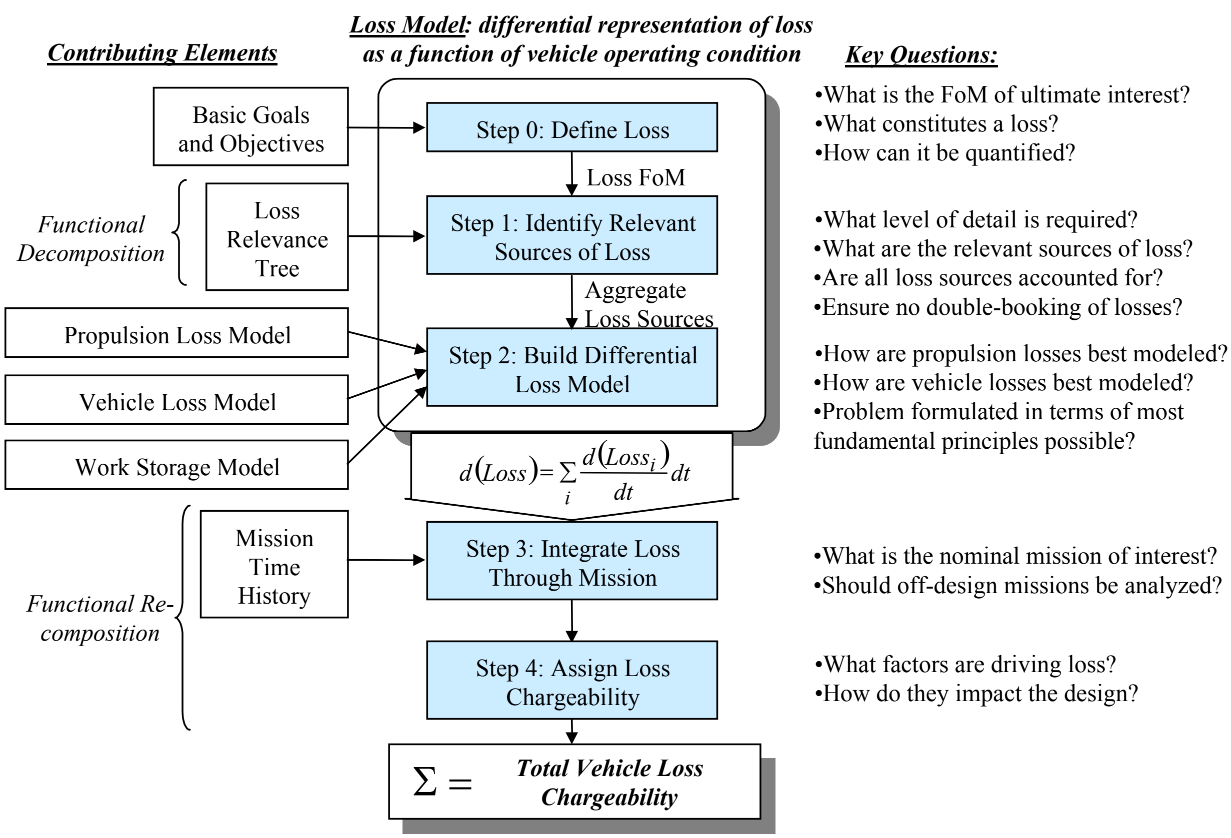


Figure 7: General Methodology for Construction of Loss Management Models.

is to allocate each loss to the factor(s) that drive it such that the true thermodynamic cost of each design decision can be understood.

Conclusions

The purpose of this paper has been to convey the motivation for applying work potential methods to aerospace vehicle design, explain how it can be used to facilitate better design decisions, and (hopefully) inspire wider interest in the continued development of these methods. Among these motivating factors are:

- *A paradigm shift in vehicle design and analysis*
  Work potential methods represent a paradigm shift in engineering philosophy away from an efficiency-based mentality towards loss-based mentality. Ultimately, efficiency in and of itself is immaterial. It is usage and loss of fuel work potential during vehicle operation that ultimately counts.
- *Complexity in vehicle design*
  As design complexity increases, aerospace systems are of necessity becoming ever more highly integrated. In the future, it may not even be possible to identify separate vehicle components, let alone define useful component efficiencies. Work potential methods avoid this limitation by dispensing with the concept of efficiency altogether.
- *Aerothermo performance as a design driver*
  Even for systems that aren't integrated, aerothermo performance is still of paramount importance and requires a uniform means of measurement in order to facilitate design of the best possible system.
- *Analysis of revolutionary technologies*
  By definition, revolutionary technologies don't have standard measures of efficiency available to gauge their performance or facilitate comparisons to conventional technologies. However, if a work potential approach is used, there is no need to create new FoMs unique to each technology. All are measured in the same units: loss of work potential.
- *Cost accounting in aerospace vehicle design*
  Cost accounting is an integral part of the business case for *every* aerospace vehicle designed today. Loss accounting should be, too; vehicle cost accounting cannot be complete without it. Loss management methods make this possible.
- *Unified weight/performance analysis of vehicles*
  Thermodynamic work potential is a physics-based, self-consistent FoM that facilitates design trades and provides the bridge linking aerothermo performance to vehicle weight (and ultimately, cost).
- *Advanced technology evaluation*
  Loss management methods provide a convenient, self-consistent framework for technology evaluation.
- *Future frontiers of aerospace vehicle design*
  The future frontiers of aerospace vehicle design are (amongst others) hypersonics and VTOL. Both are weight and performance-critical; both would benefit from application of unified weight/performance methods based on the concept of work potential.

Acknowledgements

I would like to thank the many friends and co-workers who contributed to the form and substance of this paper. In particular, we would like to thank Mr. Rob McDonald for his contributions.

References

1 Bejan, A., *Advanced Engineering Thermodynamics, 2nd Ed*., Wiley, New York, 1997.

2 Haywood, R.W., "A Critical Review of the Theorems of Thermodynamic Availability, with Concise Formulations, Part 1: Availability," *J. Mech. Eng. Sci*., Vol 16, No 4, 1974.

3 Haywood, R.W., "A Critical Review of the Theorems of Thermodynamic Availability, with Concise Formulations, Part 2: Irreversibility" *J. Mech. Eng. Sci*., Vol 16, No 4, 1974.

4 Keenan, J., "Availability and Irreversibility in Thermodynamics," *Br. J. Appl. Phys*., vol 2, July 1951.

5 Szargut, J., Morris, D.R., Steward, F.R., *Exergy Analysis of Thermal, Chemical, and Metallurgical Processes*, Hemisphere, NY, NY, 1988.

6 Ahern, J.E., *The Exergy Method of Energy Systems Analysis*, Wiley, New York, 1980.

7 Li, K.W., *Applied Thermodynamics, Availability Method and Energy Conversion*, Taylor & Francis, D.C., 1996.

8 Moran, M.J., *Availability Analysis, A Guide to Efficient Energy Use*, ASME Press, New York, 1989.

9 Nichols,J.B., "An Energy Basis for Comparison of Performance of Combustion Chambers," *Trans. of the ASME*, Jan 1953, P29-33.

10 Riggins, D., Wilson, C., Roth, B., McDonald, R., "Performance Characterization of Turboshaft Engines Via Availability and Second Law Analysis," 58th American Helicopter Society Forum, Montreal, Canada, 4-6 June 2002.

11 Roth, B.A., Mavris, D.N., "A Method for Comprehensive Evaluation of Propulsion System Thermodynamic Performance and Loss," 2001 AIAA/ASME/SAE Joint Propulsion Conference, Salt Lake City, UT, 8-11July, 2001, AIAA2001-3301.

12 Curran, Craig, *The Use of Stream Thrust Concepts for Approximate Evaluation of Hypersonic Ramjet Engine Performance*, Air Force Aero-propulsion Laboratory, Report AD-769 481, July 1973.

13 Riggins, D.W., "Evaluation of Performance Loss Methods for High-Speed Engines and Engine Components," *Journal of Propulsion and Power*, Vol. 13, No. 2, Mar-Apr 1997.

14 Roth, B.A., Mavris, D.N., "A Comparison of Thermodynamic Loss Models Suitable for Gas Turbine Propulsion," *J. of Propulsion and Power*, Vol. 17, No. 2, pp. 324-332, Mar-Apr 2001.

15 Roth, B., McDonald, R., Mavris, D., "A Method for Thermodynamic Work Potential Analysis of Aircraft Engines," Joint Propulsion Conference, Indianapolis, IN, 7-10 July 2002, AIAA2002-3768.

16 Roth, B.A., "A Work Potential Perspective of Engine Component Performance," *J. of Propulsion and Power*, Vol. 18, No. 6, pp. 1183-1190, Nov-Dec 2002.

17 Roth, B.A., Mavris, D.N., "Whither a Scheme for Vehicle Fuel Burn Accountability?," *Weight Engineering*, Vol. 60, No. 1, pp. 53-77 (see also SAWE3001), Fall 2000.

18 Roth, B.A., Mavris, D.N., "A Method for Propulsion Technology Impact Via Thernodynamic Work Potential," *J. of Aircraft*, Vol. 40, No. 1, Jan-Feb 2003.

19 Roth, B.A., "Generalized Model for Vehicle Thermodynamic Loss Management," *J. of Aircraft*, Vol. 40, No. 1, Jan-Feb 2003.